

Stump torrefaction for bioenergy application



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HIGHLIGHTS

- First study on torrefaction of stump for bioenergy application.
- Stump can achieve higher energy densification factors.
- Torrefied stump requires longer grinding time than torrefied wood.

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ABSTRACT

A fixed bed reactor has been developed for study of biomass torrefaction, followed by thermogravimetric (TG) analyses. Norway spruce stump was used as feedstock. Two other types of biomass, poplar and fuel chips were also included in the study for comparison. Effects of feedstock types and process parameters such as torrefaction temperature and reaction time on fuel properties of torrefied solid product were investigated. The study has demonstrated that fuel properties, including heating values and grindability of the investigated biomasses were improved by torrefaction. Both torrefaction temperature and reaction time had strong effects on the torrefaction process, but temperature effects are stronger than effects of reaction time. At the same torrefaction temperature, the longer reaction time, the better fuel qualities for the solid product were obtained. However, too long reaction times and/or too higher torrefaction temperatures would decrease the solid product yield. The torrefaction conditions of 300 °C for 35 min resulted in the energy densification factor of 1.219 for the stump, which is higher than that of 1.162 for the poplar wood samples and 1.145 for the fuel chips. It appears that torrefied stump requires much longer time for grinding, while its particle size distribution is only slightly better than the others. In addition, the TG analyses have shown that untreated biomass was more reactive than its torrefaction products. The stump has less hemicelluloses than the two other biomass types. SEM analyses indicated that the wood surface structure was broken and destroyed by torrefaction process.

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1. Introduction

Bioenergy has been becoming more and more widely recognized as one of the most promising renewable energy alternatives, which would sustainably replace fossil energy and meet the need in the increasing world energy demand as well as for abatement with climate change. Consequently, the extraction of logging residues (tree tops and branches) has become a common practice in the forests of northern Europe and North America [1]. In Sweden, a country of no fossil energy resources, forestry and agriculture are of considerable significance for energy supply. Already, about 20% of energy currently used comes from forestry [2].

Sweden is one of the forest-rich countries, with 22.7 billion m³ (stem volume over bark from stump to tip) [3]. The most common species, Norway spruce and Scots pine contribute 41% and 38% of the standing volume, respectively [3]. With an annual final felling area of around 200,000 ha, the harvested volume per year reached 87 million m³ between year 2005 and 2007 [4]. It was reported that Swedish forest industries are expected to face the threat of shortage of wood [5]. The first time this was forecasted was in the 1960s, when a lack of wood in the 1990s was predicted [5]. However, such a deficit had never occurred. In the 1960s, the development of nuclear power plants was in full blast in Sweden and very few people discussed about the shortage of petroleum oil and oil prices. But now again a new deficit is being predicted, exacerbated by the damage caused by the storms in January 2005 [5]. Today people even

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fear a competition for wood between the paper industry and the energy industry [5].

One way to meet the growing demand of forest biomass for energy application, without increasing the annual harvesting volume of stem wood, is to utilize stumps. By definition, the stump is all belowground and aboveground wood and bark mass of a tree beneath the merchantable timber cross-section [6]. The stump, including roots thicker than 5 cm, constitutes 23–25% of the stem volume [7]. Stump wood has been utilized during different period of various purposes, such as tar and pulp production. Today, stumps are not used for either of these purpose and be a potential source of energy. In Sweden the use of stump as fuel resource become more and more interesting [3]. The Swedish Forest Agency has estimated that stump harvesting would respond to an annual energy supply of 57 TWh/year in Sweden [4]. Furthermore, it is reported that when stumps and small roundwood from thinning are used to replace fossil fuels, the potential CO₂ reduction will be about four times as great as when only logging residues are used with a traditional chip system [8]. However, stumps have not been recognized as a bioenergy resource. It is interesting to note that although the research activity related to the use of stumps as fuel in Sweden was quite active during the last couple of years [3,8–15] no study of thermal pretreatment of stumps for energy application has been reported. Suitable methods for pretreatment of stump biomass are probably of great importance to make it accepted as fuel. It is therefore rewarding to carry out an investigation in this area for stumps.

Torrefaction is a thermochemical treatment employed to improve fuel properties of solid biomass fuel, which may be defined as a mild pyrolysis process within the temperature window of 200–300 °C, in the absence of oxygen and relatively low heating rates (<50 K/min) [16,17]. The process involves heating of the feedstock for drying, torrefaction and cooling. Similar to pyrolysis, the chemical structure of plant biomass is changed during the torrefaction. Biomass torrefaction results in products found in three phases: solid, liquid, and gas. The solid is the main product of biomass torrefaction and called torrefied biomass which has very low moisture contents and higher calorific values compared to the feedstock. Other improved fuel properties of torrefied biomass compared to the feedstock includes grindability and hydrophobicity. By cooling the exhaust steam released from biomass torrefaction processes, liquid of yellowish color is obtained from condensable gases. Non-condensable gases leave the process in the gas phase, which include carbon monoxide, carbon dioxide and little amount of methane. Typically, 70% of the feed mass is retained after torrefaction in the forms of solid products, which contain 90% of the initial energy [18]. The rest of 30% of the feed mass contains only 10% of the initial energy. The energy densification factor is commonly used to prove the improvement in energy density of torrefied solid product by torrefaction, for which the typical value is 1.3 [18].

Advantages of torrefaction of biomass for bioenergy application have been addressed in a number of published papers [16,18–21]. Prins and co-workers [16] found that it is more efficient biomass gasification via torrefaction. Li et al. [20] showed that torrefaction is able to provide a technical option for high substitution ratios of biomass in the co-firing system, up to 100% torrefied biomass without obvious decreasing of the boiler efficiency. More positively, the net CO₂ and the NO_x emissions significantly reduced with increasing of biomass substitutions in the co-firing system [20]. On the other hand, Ming and co-workers [19] demonstrated that bio-oils produced from torrefied wood have improved oxygen-to-carbon ratios compared to those from the original wood with the penalty of a decrease in bio-oil yield. The extent of this improvement depends on the torrefaction severity. It was considered that torrefaction could be a potential upgrading method to improve the quality

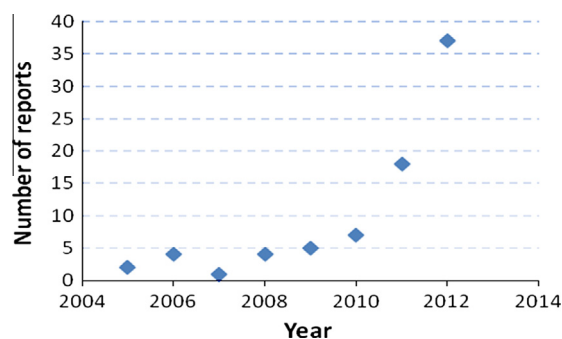


Fig. 1. Number of recent reports in biomass torrefaction by Sciencedirect.

of bio-oil, which might be a useful feedstock for phenolic-based chemicals [19]. Furthermore, in combination with pelletisation, torrefaction also aids the logistic issues that exist for untreated biomass [18].

Due to the aforementioned advantages of torrefaction, research and development activities in biomass torrefaction for energy applications worldwide were very active in the last couple of years, [18,22–36]. A quick search for the number of reports in Sciencedirect.com made by 25 September 2012, using the keyword of “torrefaction” restricted to “Abstract, Title, Keywords” fields gave the results presented in Fig. 1 on the year basis since 2005. The exponentially increasing trend of the number of reports proves the attractiveness of the technology for energy application. Different study methods and various feedstock types employed for research and development in torrefaction have been reviewed [21,37–39]. Tested feedstocks include wood, wood residues, energy crops (miscanthus, switchgrass, reed canary grass), short rotation coppice willow and poplar, and bamboo biomass material. However, none has been reported for stumps.

This present paper report results from an experimental study of biomass torrefaction, followed by thermogravimetry analysis basically for Norway spruce stump. Two other types of biomass, poplar wood and fuel chips (logging residues) were also included in the study for comparison.

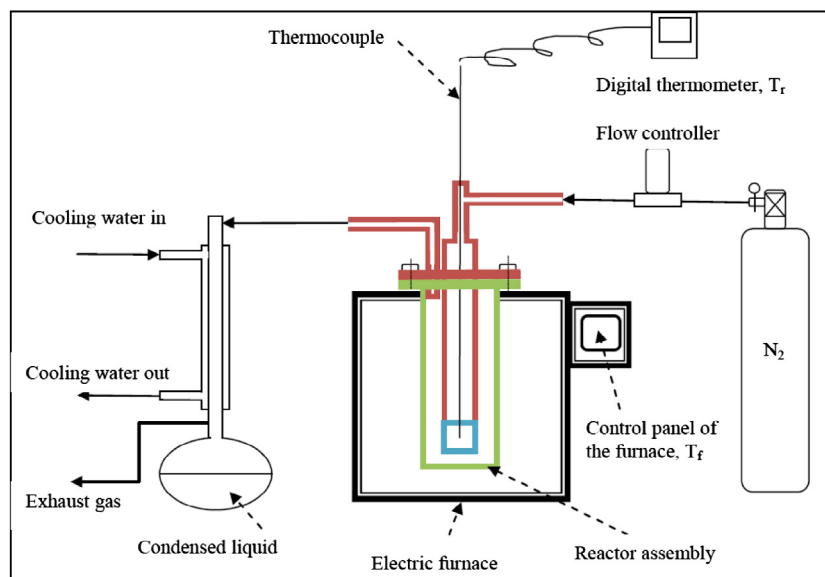
2. Experimental

2.1. Experimental setup for biomass torrefaction

Fig. 2 represents the experimental setup used for biomass torrefaction in this study, which basically includes a tubular reactor placed in an electric muffle furnace, a nitrogen gas supply system with a heating element (not shown in the figure) for gas preheating, and an water-cooled condenser connected to the outlet of the reactor. The reactor made of stainless steel was designed to fit the existing furnace, Nabertherm LH 30/12, which can be operated within a temperature range of 30–3000 °C. The main body of the reactor is about 400 mm long, and consisted of two cylinders which are assembled centrically together by a sealing mechanism on top.

The reactor is introduced into the furnace through an opening on top of the furnace, placed and held in the right position as shown in Fig. 2a by the sealing flanges. The diameter of the outer cylinder (The red color part with a closed¹ end at the bottom in Fig. 2a) is 70 mm, and that of the inner cylinder tube (Fig. 2a, the green color part with an opened end at the bottom) is 50 mm. A removable stainless steel sample cup (Fig. 2a, the blue color part)

¹ For interpretation of color in Fig. 2, the reader is referred to the web version of this article.



(a)



(b)

Fig. 2. Experimental set-up for biomass torrefaction (a: schematic view; b: lab view).

with a supporting grid at the bottom is mounted on the lower end of the inner cylinder (Fig. 2a). A thermocouple (Type K) equipped with a digital thermometer was used to monitor the samples temperature during torrefaction process, which is controlled by the furnace temperature control unit. The thermocouple, which monitors the temperature in the middle of the sample cup, is introduced into the reactor from the top as shown in Fig. 2.

2.2. Torrefaction procedure

For every torrefaction experiment, a feedstock amount of about 8 g of one type of the selected wood biomass samples (pre-dried at 105 °C for 24 h) was used. The feedstock was placed in the sample cup, which was then mounted to the inner cylinder of the reactor as described earlier. The reactor assembly completed with the outer cylinder by the top-sealing mechanism was then connected to

the inlet nitrogen gas and the condenser. Nitrogen gas (Nitrogen 4.5 from Strandmollen) was blown through the reactor at a flow rate of 5 l/min for 1 h in order to purge oxygen out of the system. After that, the nitrogen flow was reduced to 0.5 l/min before placing the reactor into the furnace, which has been preheated to a set temperature. The recorded heating rate of the sample in the reactor was about 5 °C/min. The torrefaction reaction time of 30–35 min was counted from the time when the reaction (sample) temperature (T_r) reached 200 °C to the end point when the reactor was removed from the furnace for cooling in the ambient air.

During torrefaction process, volatile compounds were released from the samples into the gas phase, following the outlet gas stream. Condensable gases were separated from the gas stream by the water-cooled condenser system and collected in the glass flask shown in Fig. 2. Non-condensable gases remained in the gas phase, leaving the process to a safe exhaust ventilation system.

The solid product remained in the sample cup after the torrefaction was collected and saved in excicators filled with silicagel for further analyses.

2.3. Instruments and analytical methods

Swedish standard methods [5–7] were employed to determine the moisture (SS 187170) and ash (SS 187171) contents of the biomass. Heating values were measured by means of a bomb calorimeter from Parr Instrument model 6300 Oxygen, following the Swedish standard method (SS 187182) [8].

A thermogravimetric analyzer (TGA) from Perkin Elmer (Pyris 1) was employed for studying non-isothermal decomposition of torrefied biomass in nitrogen, which actually measures and records the dynamics of samples weight loss with increasing temperature. The nitrogen flow was introduced into the TGA at a volumetric flow rate of 40 ml/min for all runs. The initial mass of sample for each run was in the range of 6–8 mg. The temperature was within 25–600 °C. The heating rate was at 10 K/min, 20 K/min, or 40 K/min.

For determination of heating value and TGA analysis, biomass samples must be reduced in particle size, according the standards and requirements of the instruments. For this purpose, a cutting-knife mill machine (Retsch SM 2000), integrated with a mesh sieve allowing the passage of particles smaller than 25 µm, and was used for the untreated biomass samples. A burr grinder machine Krup's GVX2 was employed to grind the torrefied biomass samples. In addition, ground torrefied biomass was sieved by means of a sieve shaker machine (Retch SV001) with four size fractions: <0.8 mm, 0.8–1 mm, 1–1.4 mm and >1.4 mm, for grindability analysis.

2.4. Feedstock

Apart from Norway spruce stump (S), two other types of biomass fuel were selected as feedstock. They were poplar wood chips (P), and fuel chips (FC). Poplar sample was taken from Helendala in southern Sweden. FC was collected from the local Swedish heating plant. The FC was freshly produced and has a nominal dimension of 20 × 40 × 3 (mm). The stump sample was the focus of this study, while the poplar and FC samples were selected for comparison. Some fuel properties of these feedstock samples are presented in Table 1. The stump and poplar samples had been dried in ambient air and stored indoor for 26 months. Therefore, the moisture contents of these samples were very low compared with the fresh fuel chips.

2.5. Torrefaction experiment matrix

Different torrefaction conditions were designed for the present study and presented in Table 2. The reaction temperature was set at 200, 250, or 300 °C. The hold time at each reaction temperature was varied between 5 and 10 min, giving two values (30 and

Table 2

Torrefaction matrix and experiment identification.

Temperature (°C)	200		250		300	
Hold time, min	5	10	5	10	5	10
Reaction time, min	30	35	30	35	30	35
Stump chip	S A5	S A10	S B5	S B10	S C5	S C10
Wood chip	P A5	P A10	P B5	P B10	P C5	P C10
Wood fuel chip					FC C5	FC 10

Table 3

Mass loss and gain in HHV of solid during torrefaction.

Temperature (°C)	200		250		300	
Reaction time, min.	30	35	30	35	30	35
<i>Mass loss of solid (g)</i>						
Stump	0.31	0.47	0.79	1.04	2.49	2.78
Poplar wood	0.42	0.59	0.98	1.08	3.02	3.43
FC					2.35	2.91
<i>Gain in HHV of solid (MJ/kg)</i>						
Stump	1.39	1.55	2.39	2.40	4.16	4.50
Poplar wood	0.01	0.06	0.69	0.79	2.64	3.12
FC					2.26	2.80
<i>Dimensionless energy densification factor</i>						
Stump	1.067	1.075	1.116	1.117	1.203	1.219
Poplar wood	1.001	1.003	1.036	1.041	1.137	1.162
FC					1.117	1.145

35 min, respectively) as the total reaction time for two torrefaction tests at each reaction temperature.

3. Results and discussion

3.1. Torrefied biomass

The solid product collected after torrefaction is hereafter referred to as torrefied biomass. By visual inspection, it is observed that the higher the torrefaction temperature, the darker the torrefied biomass was. The color of biomass torrefied at 200 °C was light brown. At 250 °C the color became browner. At 300 °C the color was dark brown. In addition, the solid product collected from biomass torrefaction at 300 °C was the most brittle, followed by the products collected from torrefaction at 250 and 200 °C. Similar changes in color of torrefied biomass were observed for increased reaction time. However, reaction time seems to have less pronounced effects on the color of the torrefied biomass than reaction temperature.

3.2. Energy densification

Table 3 represents the loss in mass and the gain in higher heating value of solids from the torrefaction experiments presented in Table 2. In addition, the energy densification factors defined as the ratio of heating values of the solids after and before torrefaction are included.

As can be seen from Table 3, for all experiments the mass loss increases with reaction temperature and/or reaction time. At the same reaction temperatures, longer hold times resulted in more mass losses of the solid. For the same reaction time, higher reaction temperatures also resulted in more solid mass losses. In addition, it was calculated that the mass loss of the solid by torrefaction was as high as 34% for the torrefaction in the most severe torrefaction conditions of the highest temperature (300 °C) and the longest reaction time (35 min, corresponding to the hold time at this temperature of 10 min).

Table 1

Proximate and ultimate analyses of the feedstock material.

Sample	HHV (MJ/kg)	Proximate		Ultimate ^b			
		Ash content ^b (wt%)	Moisture content ^a (wt%)	C (wt%)	H (wt%)	N (wt%)	O (wt%)
Spruce stump chip	20.55	8.14	7.06	49.4	5.8	0.1	40.9
Poplar wood chip	19.25	1.10	8.91				
Wood fuel chip	19.39	2.49	37.86				

HHV = Higher heating value.

^a Wet basis.

^b Dry basis.

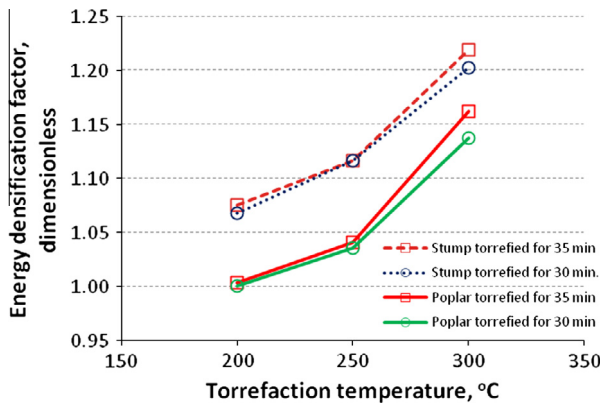


Fig. 3. Energy densification of torrefied biomass against reaction temperature.

Table 4

Grinding time for biomass torrefied in different conditions.

Sample ID	Grinding time (s)
S B5 (250 °C, 30 min)	92
S B10 (250 °C, 35 min)	90
S C5 (300 °C, 30 min)	40
S C10 (300 °C, 35 min)	30
P B5 (250 °C, 30 min)	75
P B10 (250 °C, 35 min)	72
P C5 (300 °C, 30 min)	15
P C10 (300 °C, 35 min)	12
FC C5 (300 °C, 30 min)	18
FC C10 (300 °C, 35 min)	15

For a better insight into effects of temperature and duration on torrefaction process, the dimensionless energy densification factors of stump and wood samples are graphically presented in Fig. 3.

It is observed from Table 3 and Fig. 3 that the energy densification factor increased with both increasing reaction time and torrefaction temperature. However, as can be visualized from Fig. 3, the effect of temperature is more pronounced. In the severe torrefaction conditions of 300 °C for 35 min, the energy densification factor for the stump is 1.219, followed by 1.162 for wood, and 1.145 for FC. The same trend is observed for other sets torrefaction conditions.

3.3. Grindability

As presented earlier, a coffee burr grinder machine, Krup's GVX2, was used for studying the grindability of solid products collected from the biomass torrefaction experiments. The grinder was set at an unchanged power level for grinding the same amount, 4 grams, of every sample of torrefied biomass. It should be noted that it was not possible to use Krup's GVX2 to grind untreated feedstock and those samples torrefied at 200 °C due to the lower torrefaction level of the materials and consequent difficulties encountered during grinding.

The grinding process was performed in multiple stages, between which the 1.4 mm sieve was used to collect particles smaller than 1.4 mm in diameter. The remained mass (of particles bigger than 1.4 mm) was balanced and compared with the total mass (4 g) to determine the time needed for grinding of the rest, assuming a linear correlation between mass and grinding time. The first grinding stage for the samples torrefied at 300 °C and 250 °C was set at 10 and 30 s, respectively.

Table 4 represents data obtained from the grindability tests, which shows that either increased reaction temperature or reaction time resulted in reduced grinding time, corresponding to reduced energy required to complete the grinding. However, the effect of reaction temperature was much more pronounced than that of reaction time. In addition, among the three biomass types used for the study (torrefied at 300 °C), the grinding time of the

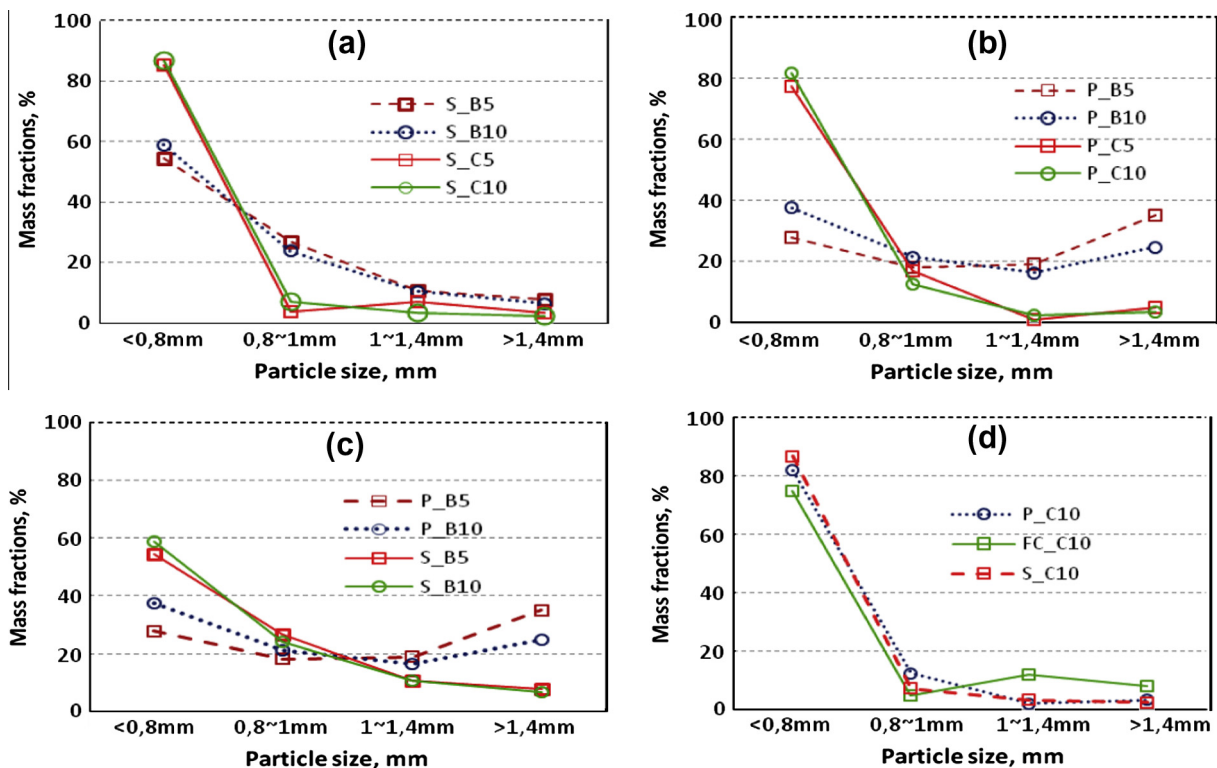


Fig. 4. Particle size distributions of torrefied biomass ground by a coffee grinder.

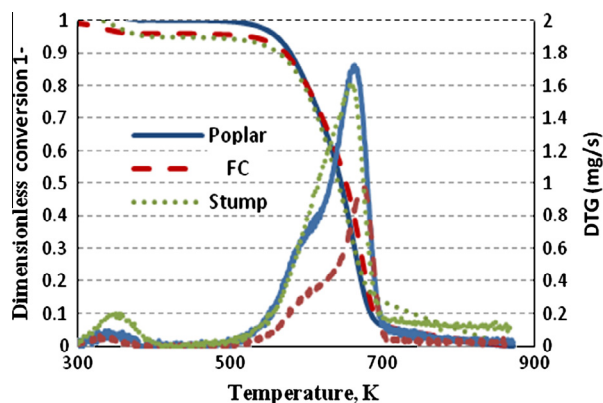


Fig. 5. TGA and DTG curves of the untreated biomass at the heating rate of 20 K/min.

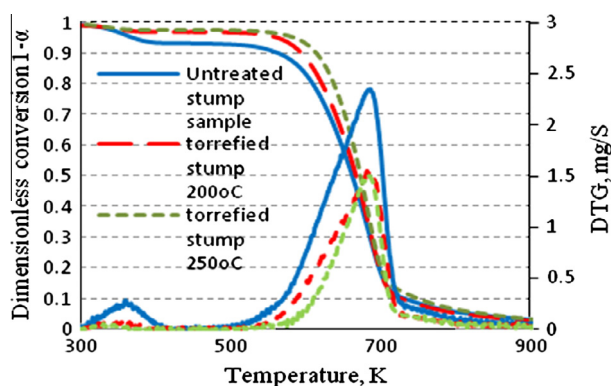


Fig. 6. TGA and DTG curves of untreated and torrefied stump in nitrogen of a gas flow rate of 40 ml/min and heating rate of 40 K/min.

stump was the longest, followed by poplar then the FC. This observation can be probably explained by the higher lignin content in the stump than in poplar and the fact that the FTC might contain softwood with relatively low lignin content.

For further evaluation of the grindability for the solid products, the powder samples collected from the grinding step were sieved and classified in four size fractions: <0.8 mm; 0.8–1 mm; 1–1.4 mm; and >1.4 mm. Fig. 4 represents the particle size distribution by mass fraction for the tests.

Fig. 4a and b is representing the particle size distribution for stump (S) and poplar (P), respectively, torrefied at 250 °C (B) and 300 °C (C), whereas Fig. 4c is for comparison of stump with poplar torrefied at 250 °C and Fig. 4d for comparison among stump, poplar, and FC, torrefied at 300 °C for 35 min (C10).

As can be seen in Fig. 4a, more than 85% of stump, torrefied at 300 °C for 30 (S-C5) and 35 (S-C10) minutes pass through the 0.8 mm sieve, whereas that for 250 °C as torrefaction temperature (S_B5 and S_B10) is more than 55%. This indicates that temperature has strong effects on the grindability. Reaction time also improves the grindability, but to a less extent. Similar trends can be observed from Fig. 4b for the case of torrefied poplar. However, both temperature and reaction time has weaker effects on the grindability than for stump, which can directly be seen in Fig. 4c representing data from grindability analysis for stump and poplar torrefied at 250 °C for 30 (S_B5 and P_B5) and 35 (S_B10 and P_B10) minutes. This trend is also valid for the torrefaction temperature of 300 °C and reaction time of 35 min as can be seen in Fig. 4d, in which data of the grindability test for FC is included. It appears that the

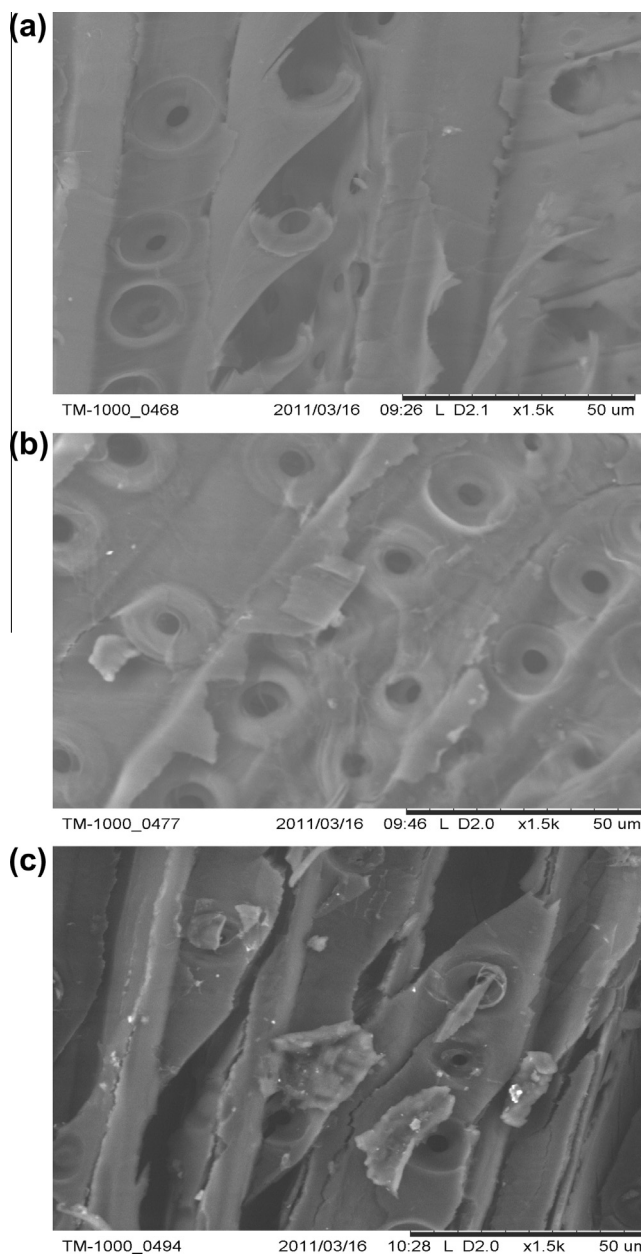


Fig. 7. SEM pictures of untreated stump and torrefied stump samples (a: Untreated stump; b: Stump torrefied at 250 °C for 35 min; c: Stump torrefied at 300 °C for 35 min).

grindability improvement of FC by torrefaction is least pronounced among the three types of feedstock tested. Furthermore, Fig. 4c indicates that stump loses its fibrous structure faster than poplar wood, being torrefied in the same conditions.

3.4. TGA and DTG curves of untreated biomass

Non-isothermal decomposition of the three untreated biomass samples was investigated in nitrogen of a mass flow rate of 40 ml/min and at three heating rates of 10, 20, and 40 K/min, using a TGA described earlier. TGA data collected from the experiments with the heating rate of 20 K/min is shown in Fig. 5, representing $(1 - \alpha)$ plotted against temperature where α is the conversion of solid, and the weight loss rate DTG (differential thermogravimetry) curves.

As can be seen from Fig. 5, there are two peaks for each DTG curve. The first tiny peak is corresponding to the drying step. The

second peak, being the main weight loss step, started at temperature of around 500 K, responsible for the thermal decomposition of biomass. The shoulder at the lower temperature side of the main peak is believed to represent the decomposition of hemicelluloses [27–29]. This shoulder seemed to be missing for the stump, which indicates that stump biomass contained less hemicellulose than the other biomass fuel types under investigation. The maximum decomposition rates was about 0.98 mg/s, 1.59 mg/s and 1.69 mg/s, which were observed to occur at 675 K, 656 K and 661 K for FC, stump and poplar, respectively. Similar trends were observed for the heating rate of 10 and 40 K/min. For example, when the heating rate increased to 40 K/min, not shown in the figure, the value of maximum mass loss rate of all three samples increased to 2.61 mg/s, 2.38 mg/s and 2.62 mg/s and the maximum point rates of decomposition occurred at 675 K, 690 K and 685 K for poplar, FC and stump respectively.

3.5. Effect of torrefaction temperature

TGA and DTG curves collected at the heating rate of 40 K/min. for untreated and torrefied stump samples are showed in Fig. 6. Clearly, untreated biomass was more reactive than its torrefaction products. In addition, the TGA curves of torrefied samples shifted towards the right with increasing torrefaction temperature, giving the DTG peaks shifting slightly away from the left to the right as well, but the peak height decreases with increasing torrefaction temperature.

In order to have a better understanding of physical changes of biomass sample during torrefaction samples of untreated stump and stump torrefied at different temperatures were examined by means of a scanning electron microscopy (SEM). Fig. 7 represents SEM pictures of untreated (a) and torrefied (b and c) stump samples. The observed increasing number of the openings on the surface of the samples examined (Fig. 7a and b) can be attributed to the formation of pathways for gas products released during torrefaction to escape from the solid bulk of biomass. In addition, the biomass structure was broken more with increasing torrefaction temperature (Fig. 7b and c).

4. Concluding remarks

A fixed bed reactor has been successfully developed for use with the muffle furnace to study the process of biomass torrefaction for fuel upgrading. It has been demonstrated that the reactor can be used for torrefying biomass in nitrogen atmosphere. The produced solids, collected from the torrefaction of stump, poplar and fuel chips have been characterized to evaluate the improvement in energy density, grindability, and thermal reactivity.

The result showed that the biomass torrefied at 300 °C for 35 min gave the highest heating value. The energy densification factor of the stump torrefied at these conditions was 1.219, which is higher than that of 1.162 for the poplar wood samples and 1.145 for the fuel chips. Both torrefaction temperature and reaction time had strong effects on the torrefaction process. At the same torrefaction temperature, the longer reaction time, the better fuel quality of the solid products was obtained. Temperature had stronger effects on the fuel properties, giving higher fuel quality of the solid product at higher temperatures for the same reaction time. However, too long reaction time and/or too higher torrefaction temperature would decrease the solid yield, which is the main product of the torrefaction process. In addition, torrefied stump requires much longer time for grinding, while its particle size distribution is only slightly better than the others.

TG analyses of the three biomass types have been performed in nitrogen environment. The results showed that the DTG curves of

the stump have a less pronounced shoulder compared with the other two samples, which indicates that the stump has less hemicelluloses than the two other biomass types. Furthermore, untreated biomass was more reactive than its torrefaction products. The TGA curves of torrefied samples shifted towards the right with increasing torrefaction temperature, giving the DTG peaks shifting slightly away from the left to the right as well, but the peak height decreases with increasing torrefaction temperature.

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